

Exploring the Gamma Ray Horizon with the
next generation of Gamma Ray Telescopes.
Part 2: Extracting cosmological parameters
from the observation of γ -ray sources

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Abstract

The potential of the new generation Cherenkov Telescopes to measure the energy spectrum of both, the already established extragalactic very high energy γ -ray emitters and the best very high energy candidates from the EGRET catalogue is discussed. By a realistic simulation of the analysis of the expected extrapolated energy spectra, it is shown that the foreseen capability and precision of these instrument to measure the Gamma Ray Horizon may open the door to competitive measurements of the cosmological parameters.

1 Introduction

Imaging Air Čerenkov Telescopes (IACT) have proven to be the most successful tool developed so far to explore the γ -ray sky at energies above few hundred GeV. A pioneering generation of installations has been able to detect a handful of sources and to start a whole program of very exciting physics studies. Nowadays a second generation of more sophisticated Telescopes is starting to provide new observations. One of the main characteristics of some of the new Telescopes is the potential ability to reduce the gamma ray energy threshold below ~ 30 GeV [1].

In the framework of the Standard Model of particle interactions, high energy gamma rays traversing cosmological distances are expected to be absorbed through their interaction with the diffuse background radiation fields, or Extragalactic Background Field (EBL), producing e^+e^- pairs. Then the flux is attenuated as a function of the gamma energy E and the redshift z_q of the gamma ray source. This flux reduction can be parameterized by the optical depth $\tau(E, z_q)$, which is defined as the number of e-fold reductions of the observed flux as compared with the initial flux at z_q . This means that the optical depth introduces an attenuation factor $\exp[-\tau(E, z_q)]$ modifying the gamma ray source energy spectrum.

The optical depth can be written with its explicit redshift and energy dependence [2] as:

$$\tau(E, z) = \int_0^z dz' \frac{dl}{dz'} \int_0^2 dx \frac{x}{2} \int_{\frac{2m^2c^4}{Ex(1+z')^2}}^\infty d\epsilon \cdot n(\epsilon, z') \cdot \sigma[2xE\epsilon(1+z')^2] \quad (1)$$

where $x \equiv 1 - \cos \theta$ being θ the angle between the photon directions, ϵ is the energy of the EBL photon and $n(\epsilon, z')$ is the spectral density at the given z' .

For any given gamma ray energy, the Gamma Ray Horizon (GRH) is defined as the source redshift z for which the optical depth is $\tau(E, z) = 1$.

In a previous work [3], we discussed different theoretical aspects of the calculation of the Gamma Ray Horizon, such as the effects of different EBL models and the sensitivity of the GRH to the assumed cosmological parameters.

In this work we estimate with a realistic simulation the accuracy in the determination of the GRH that can be expected from the observation of

the known extragalactic sources which will be, for sure, studied by the new IACTs. These sources are:

- on the one hand the very high energy gamma-ray emitting blazars already studied with the previous generation of instruments, whose spectra will be measured now up to lower energies, providing then a better lever arm for the determination of the absorption cut-off energy and,
- on the other hand the EGRET blazars which, by carefully extrapolating the measured spectrum, can be expected to have a very high energy tail, and that very likely haven't been observed at the previous generation of instruments due to the effect of the absorption cut-off.

The above sources, are distributed in a broad range of redshifts and therefore the measurement of their GRH provides a nice mapping of the GRH as a function of redshift, which we use to constraint our understanding on the EBL density and on the cosmological parameters entering the prediction of the $GRH(z)$.

It is worth to point out that besides these "bread and butter" sources, for which our assumptions are quite plausible, the reduction of the energy threshold is expected to allow the new instruments to discover a plethora of new sources which has been hidden from our observation so far. An important part of this new population is expected to be at relative large redshift ($z > 2$) where a big fraction of galaxies were AGNs and hence could produce very high energy gamma-rays. These new sources could drastically improve the results discussed here which, therefore, have to be considered as being rather conservative.

The outline of this work is the following: first we discuss the choice of the sources used and the way the spectra have been extrapolated. In section three we describe the procedure used to fit the expected spectra to the GRH and we discuss possible systematic uncertainties. Section four deals with the fit of the redshift dependence of the GRH to the cosmological parameters and the discussion on the systematic uncertainties due to our poor knowledge of the EBL density. Finally in section 5 we summarize the results obtained and explain our conclusions.

Source	Redshift z	f_o $[10^{-11}\gamma cm^{-2}s^{-1}TeV^{-1}]$	α $[\]$
Mkn 421	0.031	12.1	2.18
1ES 1426+428	0.129	0.2	2.6
Mkn 501	0.034	10.8	1.92
1ES 1959+650	0.047	-	-
PKS 2155-304	0.116	-	-
1ES 2344+514	0.044	-	-

Table 1: BL Lac objects observed in the TeV band. The absolute flux and the spectral index has been taken from flaring periods ([5, 6, 7])

2 Flux extrapolation

Although most of the conclusions of this work should apply up to to a large extent to any low-threshold installation, the specific study we present here assumes an installation on the Northern Hemisphere with a zenith threshold of about $30GeV$ such as the MAGIC Telescope.

For the first observations of any new installation, priority will be given to the investigation of the well-established extragalactic γ -ray sources which will allow to cross-check measurements with other experiments[4]. The well-established extragalactic sources observed in the Northern Hemisphere are listed in Tab.1.

Apart from these few γ -ray sources detected by Čerenkov Telescopes, the observation program will unavoidably include looking for new extragalactic γ -ray emitters. For that, one of the most plausible approaches that can be followed is based on the third EGRET catalogue [8]. It gives us the most complete and recent experimental situation for extragalactic sources at the highest satellite energies (from $100 MeV$ up to $10 GeV$). A suitable set of blazar candidates for a MAGIC-like installation can be obtained by extrapolating the Northern Hemisphere EGRET blazars fitted spectra to the MAGIC energy detection range[4].

Unfortunately the extrapolation to the MAGIC energies, both from well-established γ -ray sources and EGRET candidates, is not straight-forward since several phenomena have to be taken into account:

- On the one hand the γ -ray absorption due to pair production by the EBL, where the uncertainty is sizeable due to the poor knowledge of

the EBL.

- On the other hand, in the frame of leptonic synchrotron self-Compton (SSC) emission models, the Inverse Compton spectral break will be, for some sources, between the EGRET and MAGIC energies. With the current data, for some of the sources it is difficult to predict the energy of the spectral break with better precision than 2 orders of magnitude which, because of the sharp γ -ray spectra, may reflect into several orders of magnitude in the extrapolated flux above that energy. Moreover, these γ -ray candidates are mainly supposed to be AGN, which may have large time-variations in their flux.

For these reasons, several hypotheses are needed for the extrapolation of the flux:

- We assume that all sources are observed in a high flaring state. At first glance this may seem a very optimistic hypothesis but it is important to point out that MAGIC, and the rest of the second generation of Cerenkov Telescopes, are expected to have a large amount of source candidates to be observed and a flaring AGN will normally be a target of opportunity.
- Some assumptions about the Inverse Compton spectral break and the spectral index are also needed. Following the strategy that some AGN search study groups propose for the next generation of telescopes [4], if the spectral index measured by EGRET is larger than 2.0, we just extrapolate to higher energies with that spectra. If it is smaller than 2.0 we assume the spectral break at around 50 GeV and a 2.4 index after that, using [9]:

$$\frac{dN}{dE} = \frac{f_0 E^{-\alpha}}{(1 + (\frac{E}{E_b})^f)^{\beta/f}} \quad (2)$$

where $\alpha + \beta = \gamma$, f can go from 1 to 2.3 (we use 2.0) and $E_{peak} = E_b((2 - \alpha)/(\gamma - 2))^{1/\gamma}$

- We assume an specific model for the relevant EBL [12], which will lead to a set of given $GRH(z)$ values.

- Several characteristics of the actual IACT need to be assumed. To be more precise, the effective collection area as a function of the gamma-ray energy, the energy threshold as a function of zenith angle and the energy resolution, inspired on the MAGIC Telescope simulations are assumed (see figure 1).

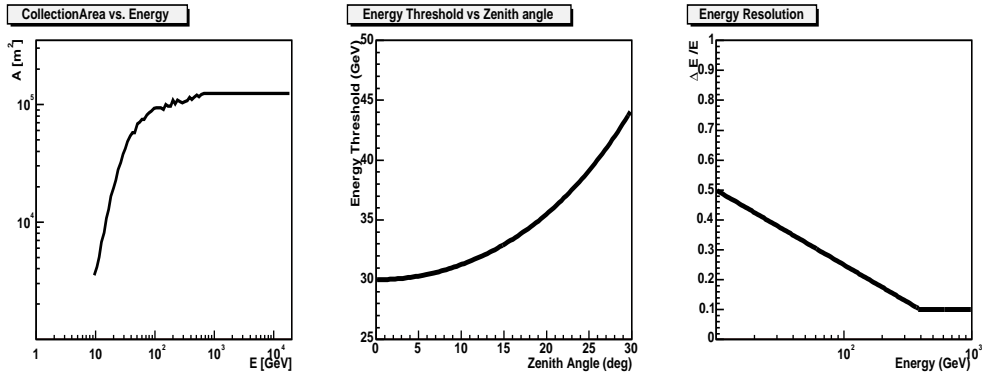


Figure 1: Assumed Telescope characteristics. Efficient Trigger Collection Area for a CT similar to the MAGIC dimensions and performance. Energy threshold as a function of zenith angle as measured by previous CT, and energy resolution from MAGIC TDR [1]

With all these hypotheses, we have simulated the flux spectrum for each source assuming 50 hours observation time and we have determined the actual precision with which it might be measured. For that the following steps have been done:

- We get the dN/dE emitted by the source using the extrapolation described above.
- The Optical Depth is applied using the EBL model detailed in [12] to get the dN/dE reaching the Earth.
- The effective collection area as a function of the gamma-ray energy is used to get the dN/dE detected by the telescope.

- Binning in energy, the number of gamma-rays is computed. This number is used to calculate the statistical error using as an error the square root of gammas. A multiplicative factor to the $\sqrt{\gamma}$ is applied to estimate the final error including the background and the telescope behaviour. This factor has been extracted from data coming from the first generation of Cerenkov Telescopes [5], hence we assume an understanding of the background and detector at the level achieved by them.
- Using the energy resolution and the number of gamma-rays per bin, we compute the energy uncertainty. Later on, this energy uncertainty is taken into account in the fit of the spectrum.

Figure 2 shows the extrapolated flux for the EGRET source EG1222+2841 assuming 50 hours observation time and the best fit to the spectral index and the spectrum cut-off energy (assuming a simple analytical expression that will be justified below) after the above steps have been completed.

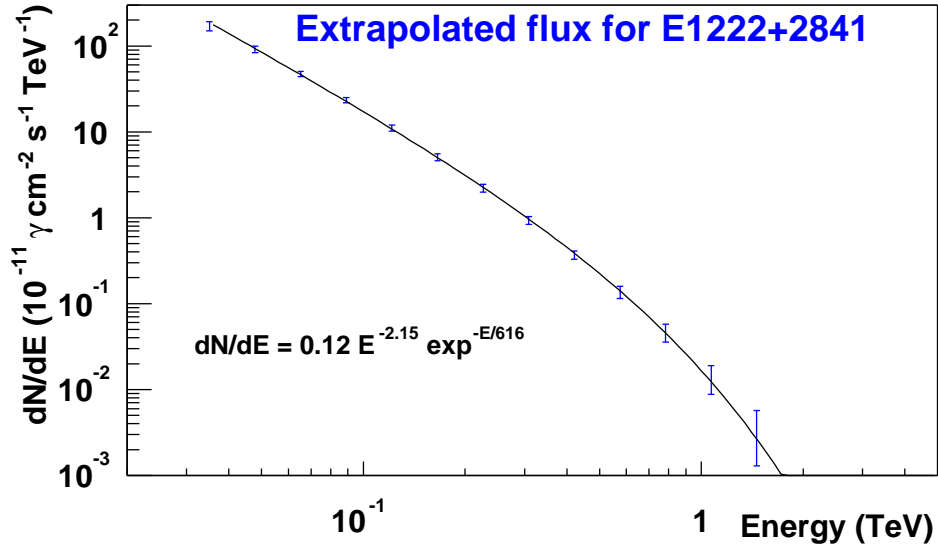


Figure 2: Extrapolated flux for source E1222+2841

3 Gamma Ray Horizon fits

The differential flux seen at the earth should actually be:

$$\frac{dN}{dE} = \left(\frac{dN}{dE}\right)_{unabsorbed} \cdot e^{-\tau(E,z)} \quad (3)$$

The actual dependence of τ on E and z is quite complex and cannot be cast on a simple analytical expression [3]. Nevertheless, in first approximation, the exponential suppression term can be expressed as an e-fold reduction in the energy E_0 , which will coincide with the Gamma Ray Horizon energy. Moreover, in case the threshold energy of the Telescope is well below the spectrum cut-off energy, the emitted flux dN/dE can be well approximated for most of the sources by a power law. Therefore, in first approximation one gets an analytical expression that can be used to fit the spectrum and get the energy of the GRH (E_0):

$$\frac{dN}{dE} = f_0 \cdot E^{-\alpha} \cdot e^{-(\frac{E}{E_0})^\beta} \quad (4)$$

It is true that at the energy range that MAGIC will reach one can argue that in some cases the effect of the Inverse Compton spectral break may play a role. Actually as it seen in the section 2 we took into account that, whenever it was needed. Unfortunately the expected energy threshold for MAGIC is so close to the assumed break energy that there is not lever arm to get information on that with the assumed 50 hours observation time. Therefore, the previous equation has been used to fit the spectrum and get the GRH energy for all the extrapolated sources. The error due to this simplification has been included in the systematics.

The result and precision of the GRH energy fitted for every source as well as the theoretical predictions are shown in the table 2.

4 Cosmology

As discussed already in [3], from the expression of the Optical Depth (equation 1), it is clear that some fundamental cosmological parameters such as the Hubble constant and the cosmological densities play an important role in the calculation of the GRH, since:

Source Name	z	$E_0(GeV)$	$\sigma_{E_0}(GeV)$
Mrk 421 , 3EG J1104+3809	0.031	5203	448
W Comae , 3EG J1222+2841	0.102	615.7	23.9
3EG J1009+4855	0.200	355.2	2.6
OJ+287 , 3EG J0853+1941	0.306	255.3	9.1
4C+15.54 , 3EG J1605+1553	0.357	224.3	7.7
3EG J0958+6533	0.368	219.1	15.2
3EG J0204+1458	0.405	201.7	12.7
3EG J1224+2118	0.435	189.1	21.6
3C 279 , 3EG J1255-0549	0.538	155.4	1.3
3EG J0852-1216	0.566	148.0	2.6
4C+29.45 , 3EG J1200+2847	0.729	114.4	3.2
CTA026 , 3EG J0340-0201	0.852	96.61	1.76
3C454.3 , 3EG J2254+1601	0.859	95.74	0.73
3EG J0952+5501	0.901	90.82	7.8
3EG J1733-1313	0.902	90.71	4.8
OD+160 , 3EG J0237+1635	0.940	86.68	1.00
3EG J2359+2041	1.070	75.31	7.4
3EG J0450+1105	1.207	66.58	3.8
3EG J1323+2200	1.400	57.87	2.4
3EG J1635+3813	1.814	46.69	1.8
Mrk 501	0.034	4274	115
1ES J1426+428	0.129	504.4	61.1

Table 2: GRH fit predictions for the 22 sources considered.

$$\frac{dl}{dz} = c \cdot \frac{1/(1+z)}{H_0[\Omega_M(1+z)^3 + \Omega_K(1+z)^2 + \Omega_\Lambda]^{1/2}} \quad (5)$$

Therefore the measurement of the GRH for sources at several redshifts will open the possibility to obtain constraints in some fundamental cosmological parameters [3].

Conceptually the measurement of the GRH as a function of the redshift, provides a new distance estimator which has the following features:

- It is independent and behaves differently from the luminosity-distance relation currently used by the Supernovae 1A observations (see [3]).
- It does not rely on the existence of a time-independent standard-candle as do the Supernovae 1A measurements, although it relies on the existence of a cosmological infrared EBL which, in first approximation, is assumed to be uniform and isotropic at cosmological scales.

- It uses Active Galactic Nuclei as sources, and therefore may allow the study of the expansion of our universe up to the highest observable redshifts. In this sense this method might complement the picture provided by Supernovae 1A exploring the farthest universe.

In figure 3, the simulated GRH energy measurements and their estimated expected uncertainties are plotted together with the theoretical GRH predictions for several extreme hypothetical universes.

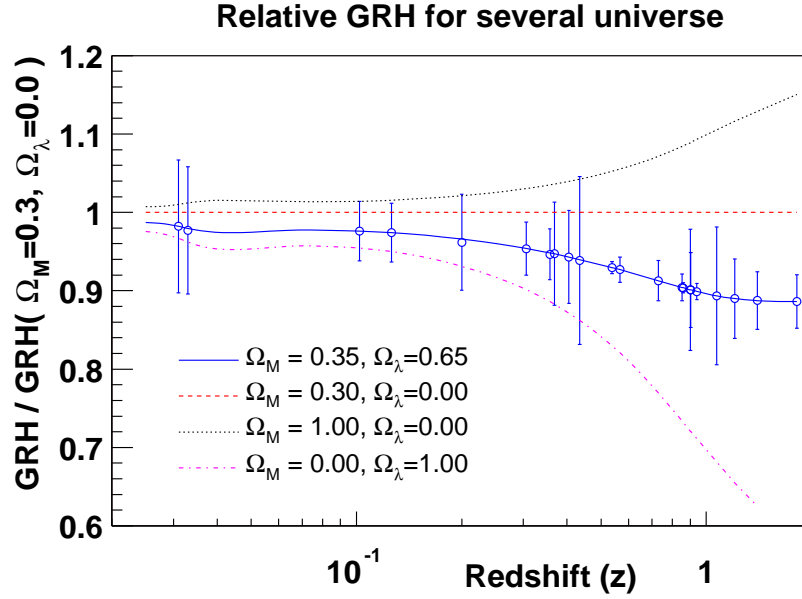


Figure 3: Simulated GRH measurements and the GRH predictions for different universe models

The prediction of the GRH as a function of the redshift has basically only the following parameters: the Hubble constant, the cosmological densities and last, but not least, the EBL density spectrum as a function of redshift. Assuming the later perfectly known, one can try to use the simulated measurements of table 2 to fit the cosmological parameters. This is a four-parameter fit which, if tried with "brute-force" turns out to be inviable. Instead we've followed the strategy developed in [10] for a similar problem, which consists on the use of a multi-dimensional interpolating routine based

upon the algorithms of [11]. We have checked that within the parameter intervals relevant for the fits discussed in this work, that interpolation produces results which reproduce the exact predictions with the required accuracy.

In Figure 4, the $\Delta\chi^2 = 2.3, 5.99$ and 9.21 contours, corresponding to a two-parameter confidence areas of 68%, 95% and 99% respectively in the $\Omega_M - \Omega_\lambda$ plane are plotted. Despite the GRH measurements allow also to obtain some information on the Hubble constant, experiments looking to a closer distance can do it much better. For this reason the best fit confidence region has been computed assuming an external constrain in H_0 of 4.0 Km s /Mpc [13].

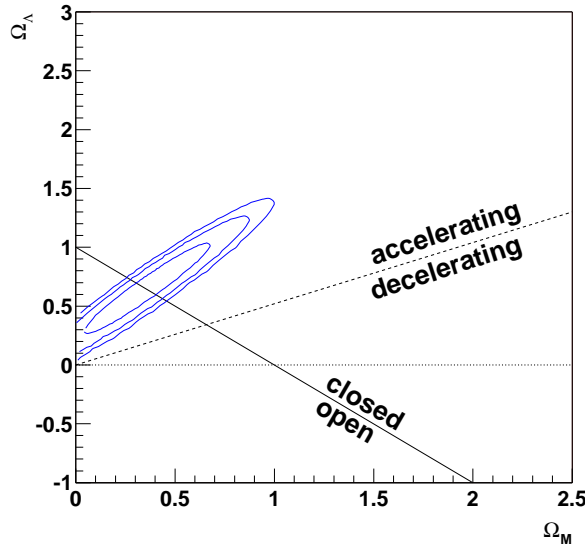


Figure 4: Expected contour levels of 68%, 95% and 99% for the $\Omega_M - \Omega_\lambda$ plane based on the GRH.

These contours can be compared with the results from the combination of all Supernovae 1A measurements at relatively low redshift [14] to show that there is roughly a factor 2 improvement in the expected uncertainties. Actually, these contours have a size similar to the one recently claimed by the use of very distant Supernovae [15], which shows the need for looking at large redshifts (1-2) to improve in the measurement of Ω_M and Ω_λ . It is also

worth to point out that it will also be a significant measurement taking into account other current techniques [16, 17], since the explored parameter space is rather orthogonal.

4.1 Systematics

So far mostly statistical uncertainties have been taken into account. This could be unrealistic since large systematical uncertainties could eventually appear in some of the assumptions taken.

Two kind of systematic uncertainties have been taken into account:

- On the one hand, "experimental" systematics, which we believe will be dominated by the global energy scale, which enters directly in the GRH determination and is not very well known in Cherenkov Telescopes. We have assumed a conservative 15% global energy scale systematic uncertainty.
- On the other hand, "theoretical" systematics. As already stated, the GRH behavior with the redshift does not depend only on the cosmological parameters but also on the EBL density as a function of redshift assumed. The fact that, at present, the EBL is not well measured at the relevant energy range, and its redshift dependence is not well known, forces the use of different models which differ substantially in their predictions [18, 12]. The assumption of different EBL models is expected to produce important uncertainties in the determination of these cosmological parameters.

For what concerns the "experimental" systematics, figure 5 illustrates the modest size of the estimated effect due to the effect of the global energy scale and the simplifications done in the spectral fit.

For what concerns the "theoretical" systematics, the situation is more complex. To estimate them, we have used a set of models [19] which are somehow representative of the different approaches followed up to now for the prediction of the EBL and that, so far, have not been excluded by the existing relevant observations. Each model has a rather complex set of assumptions and physics ansatzs based upon some observations and therefore it does not look feasible to parameterize all them in a simple manner which would allow

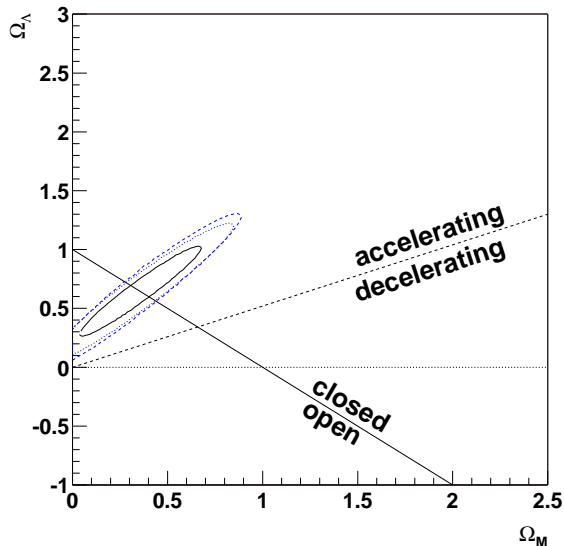


Figure 5: Contour levels of 68% for the $\Omega_M - \Omega_\lambda$ plane showing the effect of including different "experimental" systematics. Solid line is the contour with only statistical errors. Dotted line includes the error due to the fit simplification. Finally, in the dashed line it is also included the systematic due to the energy scale.

us to fit them to the GRH data. The contours obtained for the different EBL models are shown in figure 6. Nevertheless, there are a couple of facts that can be taken into account to try to obtain a plausible estimate of their effect in the cosmological parameter fit.

- For most of the relevant parameters in the EBL prediction (star formation rate, warm dust in the interstellar medium, IR extragalactic background, ...) the most discriminating region is at low redshift ($z > 0.1$) as can be seen in figure 7.
- The redshift evolution of the predicted GRH for the different models in figure 7 shows that above redshift 0.1 the main parameter to take into account is the UV density (UV model and high UV model).

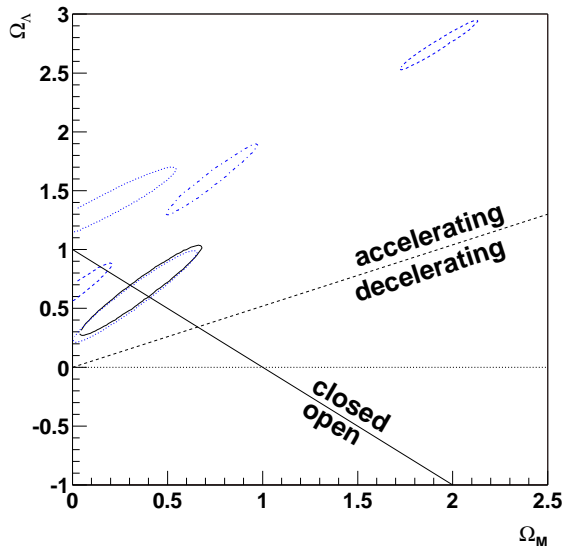


Figure 6: Contours levels of 68% for several EBL models.

Since most of the sensitivity to the Ω_M and Ω_λ cosmological parameters is at large redshift (see fig.3), we've taken the following approach to make a conservative estimate of the systematic uncertainties induced by the present knowledge of the EBL:

- We have excluded the first two points (low redshift AGNs) from the cosmological parameter fits assuming that they will be primarily used to discriminate among different EBL modeling approaches.
- We have used the remaining points (high redshift AGNs) to fit the cosmological parameters. In order to quantify the additional uncertainty due to the remaining EBL model dependence, we've introduced in the fit as an additional parameter the amount of UV background (using the same approach than in [19]).

Unfortunately, this additional parameter turns out to be rather correlated with the Ω_M and, fundamentally through this correlation, there is not hope to get information on Ω_M and Ω_λ without constraining the UV background.

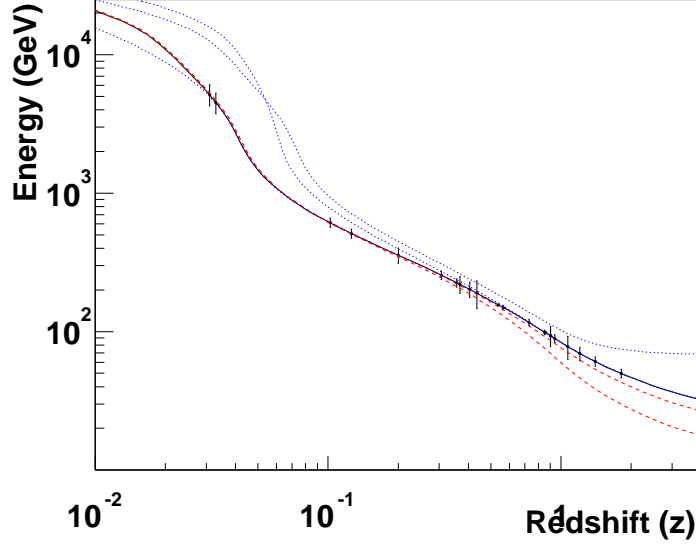


Figure 7: GRH predictions as a function of redshift for several EBL models compared with the expected experimental accuracies of the GRH measurements for the different AGNs considered in this work. Blue dotted lines are for EBL models with low Star Formation Rate, warm dust and low IR background light. Red dashed lines only differ from the best fit model, which is the trend followed by the expected data points, by the amount of UV background light.

In figure 8 it is shown how the contours in the $\Omega_M - \Omega_\lambda$ degrade for different constraints. Assuming the possibility to measure with an independent technique the UV background at 15% level, the quality of the Cosmological Parameter fits is still very competitive.

At any rate, the launch of some new missions to study both the UV [20] background and the Star Evolution are scheduled for the next few years, and they may shed new light into our understanding of the EBL in the relevant energy region and therefore help to substantially reduce the estimated systematical uncertainties.

It is worth to point out here that, turning the other way around the argument followed in this work, the mapping of the redshift evolution of the

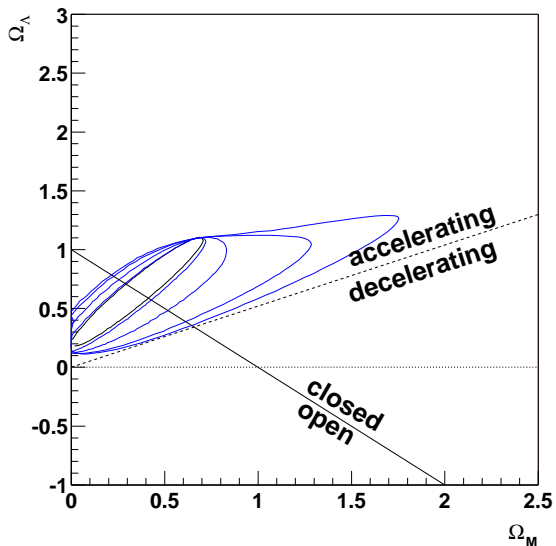


Figure 8: Contour levels of 68% for the $\Omega_M - \Omega_\lambda$ plane for the fit with redshift $z > 0.2$ sources in which an additional constrained (at 5, 15, 25 and 30% levels) parameter has been introduced to account for the uncertainty in the UV background.

GRH has been suggested already several times in the literature as a way to constraint ONLY the EBL spectrum and its redshift dependence provided that one assumes the constraints in the cosmological parameters coming from other cosmology measurements. In the strategy suggested in this work, it is already suggested the use of the low-redshift GRH observations, which are rather insensitive to the cosmological densities, to constraint the low-redshift predictions of the EBL models. If one really wants to use the gamma-ray absorption to measure values for the EBL at different redshifts, the whole optical depth will be needed. For that one needs to extract it from the spectrum distortion knowing the original source spectrum, which may involve source-dependent models for the extrapolation of the undistorted spectrum. On the other hand, the approach discussed in this paper relies on the hope that a more direct measurement of the EBL and its redshift evolution in the relevant range becomes available in the coming years.

5 Conclusions

Based on the extrapolation of the established extragalactic TeV emitters and the best EGRET candidates to emit at the energy range the new low-threshold IACTs such as the MAGIC Telescope will be able to measure, the measurement of the Gamma Ray Horizon for sources in a large redshift range (0.031 to 1.8) has been simulated.

It has been shown that percent level GRH measurements with observation times of about 50 hours are expectable for some sources, providing therefore a good mapping of the GRH as a function of the redshift. These determinations will provide a new distance estimator which has the following features:

- It is independent and behaves differently from the luminosity-distance relation currently used by the Supernovae 1A observations (see [3]).
- It does not rely on the existence of a time-independent standard-candle as do the Supernovae 1A measurements, although it relies on the existence of a cosmological UV to infrared EBL which, in first approximation, is assumed to be uniform and isotropic at cosmological scales.
- It uses Active Galactic Nuclei as sources, and therefore may allow the study of the expansion of our universe up to the highest observable redshifts. In this sense this method might complement the picture provided by Supernovae 1A exploring the farthest universe.

A multi-parameter fit of the cosmological parameters to $GRH(z)$ is shown to provide at the statistical level a determination of Ω_M v.s. Ω_Λ which is at the level of the best present results from the combined Supernovae 1A observations.

In addition, the reduction of the energy threshold is expected to allow the new instruments to discover a plethora of new sources which has been hidden from our observation so far. An important part of this new population is expected to be at relative large redshift ($z > 2$) where a big fraction of galaxies were AGNs and hence could produce very high energy gamma-rays. These new sources could drastically improve the results discussed here which, therefore, have to be considered as being rather conservative.

In addition, a first estimation of the main systematic uncertainties from experimental and theoretical origin has been presented. The main experimental systematic has been estimated to be the global energy scale of the

IACTs which, as shown has a very modest effect on the cosmological parameter fits.

The main theoretical systematic comes from the assumption of the UV to infrared Extragalactic Background Light (EBL) and its redshift evolution, for which several models have been explored in this work. The systematic uncertainty coming from considering all these models has been shown to be the dominant uncertainty in the present situation.

These models have a quite broad spectrum of predictions in our region of interest. There already exist which some experimental data able to constraint these models precisely in that region. And, there is a good hope that the situation may be better in the near future due to the lunch of new missions to explore in detail the UV to infrared universe and to the impressive improvement that the understanding of structure formation in the universe is experimenting within the last few years.

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